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14. ABSTRACT

This project aims to address and solve key sensing, learning, strategic decision and resource allocation issues in the design of a cognitive tactical radio (CTR). Such a tactical radio has superior ability in learning its spectrum environment, possibly highly dynamic, and can behave intelligently and strategically in the presence of multiple other completing or collaborating tactical radios. Our research agenda consists of the following four integral tasks: (T1) robust spectrum sensing of multiple channels using adaptive group testing, (T2) multiuser learning and its

15. SUBJECT TERMS

Cognitive tactical radio, sensing, learning, strategic decision, resource allocation

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Report Title

Cognitive Tactical Radios: Cognition Through Learning and Strategy (CLearStrategy)

ABSTRACT

This project aims to address and solve key sensing, learning, strategic decision and resource allocation issues in the design of a cognitive tactical radio (CTR). Such a tactical radio has superior ability in learning its spectrum environment, possibly highly dynamic, and can behave intelligently and strategically in the presence of multiple other completing or collaborating tactical radios. Our research agenda consists of the following four integral tasks: (T1) robust spectrum sensing of multiple channels using adaptive group testing, (T2) multiuser learning and its regret, (T3) convergence of multiuser learning to pure Nash equilibrium (PNE) in spatial congestion games, and (T4) globally optimal spectrum sharing through game-theoretic and mechanism design-theoretic frameworks. We have successfully completed these tasks. The research undertaken by the project can have significant impact both theoretically and in practice. In particular, our contributions in the areas of game theory and online learning theory are quite general and therefore more broadly applicable to other areas of networking as well as decentralized multi-agent systems, well beyond the context of cognitive radio design.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
12/08/2012	6.00	Cem Tekin, Mingyan Liu, Richard Southwell, Jianwei Huang , Sahand H. A. Ahmad . Atomic Congestion Games on Graphs and Their Applications in Networking, IEEE/ACM Transactions on Networking, (10 2012): 1541. doi:
12/08/2012	17.00	Cem Tekin, Mingyan Liu. Online Learning of Rested and Restless Bandits, IEEE/ACM Transactions on Networking, (08 2012): 5588. doi:

TOTAL: 2

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
12/08/2012	7.00	Cem Tekin, Mingyan Liu. Performance and convergence of multi-user online learning, to appear as a chapter in the book "Mechanism and Games for Dynamic Spectrum Allocation" to be published by Cambridge University Press. , . : Cambridge University Press, Cambridge University Press
12/08/2012	15.00	Cem Tekin, Mingyan Liu. Adaptive Learning of Uncontrolled Restless Bandits with Logarithmic Regret, Allerton. 2011/09/29 00:00:00, . : ,
12/08/2012	16.00	Yang Liu, Mingyan Liu, Jing Deng. Is Diversity Gain Worth the Pain, IEEE INFOCOM Mini-Conference. 2012/03/26 00:00:00, . : ,
12/08/2012	12.00	Yi Gai, Bhaskar Krishnamachari, Mingyan Liu. Online Learning for Combinatorial Network Optimization with Restless Markovian Rewards, IEEE SECON. 2012/06/19 00:00:00, . : ,
12/08/2012	10.00	Mingyan Liu, Cem Tekin. Approximately Optimal Adaptive Learning in Opportunistic Spectrum Access, IEEE INFOCOM . 2012/03/26 00:00:00, . : ,
12/27/2011	2.00	Cem Tekin, Mingyan Liu. Adaptive Learning of Uncontrolled Restless Bandits with Logarithmic Regret, Annual Allerton Conference on Control, Communication, and Computation (Allerton). 2011/09/29 00:00:00, . : ,
12/27/2011	4.00	Mingyan Liu, Cem Tekin. Approximately Optimal Adaptive Learning in Opportunistic Spectrum Access, IEEE Annual International Conference on Computer Communications (INFOCOM). 2012/03/26 00:00:00, . : ,
12/27/2011	5.00	Yang Liu, Mingyan Liu, Jing Deng. Is Diversity Gain Worth the Pain: Performance Comparison Between Opportunistic Multi-Channel MAC and Single-Channel MAC, IEEE Annual International Conference on Computer Communications (INFOCOM) Mini-Conference. 2012/03/30 00:00:00, . : ,

TOTAL: **8**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
12/08/2012	14.00	Bhaskar Krishnamachari, Mingyan Liu, Yi GAI. Combinatorial Network Optimization: A Restless Multi-Armed Bandit Approach, IEEE/ACM Transactions on Networking (10 2012)
12/08/2012	11.00	Cem Tekin, Mingyan Liu. Online Learning in Decentralized Multiuser Resource Sharing, IEEE Journal of Selected Topics in Signal Processing (11 2012)
12/08/2012	9.00	Yang Liu, Mingyan Liu, Jing Deng. Evaluating Opportunistic Multi-Channel MAC: Is Diversity Gain Worth the Pain?, IEEE Journal Selected Areas in Communication (10 2012)
12/27/2011	1.00	Cem_Tekin, MIngyan_Liu. Online Learning of Rested and Restless Bandits, IEEE Transactions on Information Theory (12 2011)
12/27/2011	3.00	Cem Tekin, Mingyan Liu, Richard Southwell , Jianwei Huang , Sahand H. A. Ahmad. Atomic Congestion Games on Graphs and its Applications in Networking, IEEE Transactions on Networking (12 2011)

TOTAL: **5**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

The following paper received "Honorable Mention" (Best Paper Runner-up) at the IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), June 2012, Seoul, Korea.

Y. Gai, B. Krishnamachari and M. Liu, “Online learning for combinatorial network optimization with restless Markovian rewards."

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yang Liu	0.30	
Cem Tekin	0.50	
FTE Equivalent:	**0.80**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Mingyan Liu	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Table of Content:

(1) Statement of the problem studied

This project aims to address and solve key sensing, learning, strategic decision and resource allocation issues in the design of a cognitive tactical radio (CTR). Such a tactical radio has superior ability in learning its spectrum environment, possibly highly dynamic, and can behave intelligently and strategically in the presence of multiple other completing or collaborating tactical radios. The principal goal is for a large number of such radios to coexist efficiently in the presence of either hostile or non-responsive devices.

This project is of significant relevance to the Army. Wireless spectrum is a limited resource and is getting ever more crowded. How to control and manage spectrum congestion and interference thus has become a critical issue for data networking. Recent advances in software defined ratio (SDR) and cognitive ratio (CR) have opened up new avenues of addressing the problem. However, a large part of existing literature on CR focuses on a primary-secondary user model that is more relevant to civilian/commercial applications than to military networks. In terms of theoretical foundations, while the research community has accumulated a large volume of results on spectrum sensing, the learning and reasoning aspects having been relatively lagging.

(2) Challenges

We note that the challenges facing the Army in the context of cognitive tactical radio design are unique: (1) the spectrum environment that the military faces is highly dynamic, frequently adversarial, and often unknown, due to the existence of hostile devices, and (2) the type of wireless devices involved are often highly heterogeneous and are used for drastically different applications with different load and quality of service requirements which may or may not be known to each other (i.e., they are private information). Consider for instance the personal area/body sensor networks used by military personnel. Soldiers are equipped with wireless sensors that can, monitor their health status and provide such data in real time to a remote command and control center, or monitor the immediate environment of the person to assist real-time decision-making. This is in addition to other wireless voice/video/data communication devices the soldier is equipped with. In such scenarios, many of these devices will likely belong to different networks, each serving a different purpose and each having its own data characteristics and performance requirements, but also likely having to share the same spectrum. Therefore good design that allows efficient spectrum sharing and coexistence among highly heterogeneous devices and networks in a highly dynamic environment becomes critical for military networks, and this is what the project intends to accomplish.

(3) Approach taken by the project

Our approach consists of a comprehensive framework, whereby a CTR's cognitive ability is built on the following key components: (1) information acquisition through highly efficient and robust sensing algorithms that exploit sparse and compressive sampling theory, group testing theory and robust algorithm design in an adversarial setting; (2) learning through state-of-the-art online algorithm design; and (3) strategic decision making through game-theoretic and mechanism design-theoretic methods. Accordingly, our research agenda consists of the following four integral tasks: (T1) robust spectrum sensing of multiple channels using adaptive group testing, (T2) multiuser learning and its regret, (T3) convergence of multiuser learning to pure Nash equilibrium (PNE) in spatial congestion games, and (T4) globally optimal spectrum sharing through game-theoretic and mechanism design-theoretic frameworks.

(4) Summary of the most important results

There are four research tasks under this project (T1-T4 as listed above). We have successfully completed these tasks. Our most important results are summarized in the following. Firstly, we are one of the first to study robust spectrum sensing in an adversarial setting, which makes our results relevant in a hostile environment and ensures that our algorithms can function in the worst-case scenarios. Secondly, we developed a number of algorithms for decentralized multi-user online learning with order-optimal regret in two cases: (1) when the optimal channel allocation is orthogonal, i.e., no more than one user on a channel (reference 2 below), and (2) when the optimal channel allocation may involve sharing among users (reference 1, 6 and 7 below). To the best of our knowledge, this second case has not been studied before. Thirdly, we also successfully developed adaptive learning algorithms that can achieve order-optimal strong regret, which is with respect to the best dynamic policy (see reference 11 below). Most the work in the literature (including some of our own) focuses on weak regret, which is with respect to the best static policy (or single-action policy). Our result is therefore much stronger in terms of the performance of the learning algorithm (at an expense of increased, though quantifiable, computational complexity).

(5) List of publications

Book chapter:

1. C. Tekin and M. Liu, “Performance and convergence of multiuser online learning and its applications in dynamic spectrum sharing,” to appear in the book Mechanism and Games for Dynamic Spectrum Allocation, to be published by Cambridge University Press.

Journal papers, appeared and under submission:

2. C. Tekin and M. Liu, “Online Learning of Rested and Restless Bandits,” in IEEE Transactions on Information Theory, vol. 58, no. 8, pp 5588-5611, August 2012.
3. Y. Liu, M. Liu and J. Deng, “Is diversity gain worth the pain: performance comparison between opportunistic multi-channel MAC and single-channel MAC,” under submission to the IEEE Journal on Selected Areas in Communications (JSAC).
4. C. Tekin, M. Liu, R. Southwell, J. Huang, and S. Ahmad, “Spectrum sharing as spatial congestion games,” IEEE Transactions on Networking, vol. 20, no. 5, pp. 1527-1540, October 2012.
5. Y. Gai, B. Krishnamachari and M. Liu, “Combinatorial Network Optimization: A Restless Multi-Armed Bandit Approach”, submitted to IEEE Transactions on Networking, October 2012.
6. C. Tekin and M. Liu, “Online learning in decentralized multiuser resource sharing,” submitted to IEEE Journal of Selected Topics in Signal Processing (JSTSP), October 2012.

Conference publications:

7. C. Tekin and M. Liu, “Online learning in decentralized multi-user spectrum access with synchronized explorations,” in IEEE Military Communication Conference (MILCOM), October 2012, Orlando, FL.
8. Y. Gai, B. Krishnamachari and M. Liu, “Online learning for combinatorial network optimization with restless Markovian rewards,” IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), June 2012, Seoul, Korea. [Best Paper Runner-up]
9. C. Tekin and M. Liu, “Approximately optimal adaptive learning in opportunistic spectrum access”, in IEEE Annual Conference on Computer Communications (INFOCOM), March 2012.
10. Y. Liu, M. Liu and J. Deng, “Is diversity gain worth the pain: performance comparison between opportunistic multi-channel MAC and single-channel MAC,” in IEEE Annual Conference on Computer Communications (INFOCOM) mini-conference, March 2012.
11. C. Tekin and M. Liu, “Adaptive learning of uncontrolled restless bandits with logarithmic regret”, in Annual Allerton Conference on Communication, control and Computing (Allerton), pp. 1-8, September 2011, Allerton, IL.

(6) Collaborations and Leveraged Funding

1. We are collaborating with Prof. Jianwei Huang at the Chinese University of Hong Kong, on research issues related to the convergence and performance properties of congestion games, and their generalization to graphs. Results have been reported in paper 4 listed above and are related to task (T3).
2. We are collaborating with Prof. Bhaskar Krishnamachari at the University of Southern California, on the use of our online learning algorithms in a combinatorial and multiuser setting. This result has been reported in papers 5 and 8 listed above, and is related to task (T2).
3. We are collaborating with Prof. Jing Deng at the University of North Carolina, Greensboro, on the performance comparison study of multi-channel opportunistic MAC vs. single-channel MAC. Preliminary result is included in papers 3 and 10 listed above and is related to task (T4).
4. We have on-going collaboration with Prof. Romesh Saigal at the Industrial and Operations Engineering Department at the University of Michigan on refining a stochastic differential equation (SDE) based spectrum model we developed earlier. This model is going to be used for the evaluation of algorithms developed under this project.

(7) Conclusion

We have successfully completed the proposed research tasks, and made significant progress toward our ultimate goal of building a versatile and agile cognitive radio. The research undertaken in this project is of significant relevance to the Army, and makes significant contribution to both the theory and practice of cognitive radios.

Technology Transfer